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Advances in Solar Photovoltaics:
Technology Review and Patent Trends

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ABSTRACT

Against the pressing challenges of climate change and fossil fuel depletion, renewable energy sources such as solar photovoltaics (PV) are considered a clean and sustainable alternative. PV technologies have grown into a substantial field of research and development through large stocks of scientific publications and patents. Besides cell technologies, the balance of system (BoS) components such as panels, electronics and energy storage form an important research area. The present article studies the development of the PV technological system using patent indicators. It is composed of three parts: First, it defines the system by thoroughly reviewing the various cell and BoS technologies. Second, it introduces a novel methodical approach for identifying its relevant patents. In that sense, the paper contributes with an accurate inventory of international patent classes for PV system. Finally, the geographical, organizational and technical trends over the past six decades are analysed along with a review of the most influential inventions. The analysis shows that 95% of the PV patent applications are filed by inventors from seven countries: Japan, Korea, China, USA, Germany, Taiwan, and France. Most patents are filed by companies and related to thin-film and crystalline-silicon cells as well as panel encapsulation and supporting structures. The analysis reviews the quantity, quality and technological specialization within countries' patent profiles. It further provides an overview of the technological landscape and freedom-spaces available for manufacturers.

KEYWORDS

Solar Photovoltaics; Renewable Energy; PV Cell Technologies; Balance of System; IPC Classes Inventory; Patent Trends; Sectoral Identification

Information Box: Broader Context

Climate change is the major challenge of the world according to the United Nation's millennium project. In fact, the global average temperature has increased by one degree Celsius over the last century, with CO_2 emissions resulted from fossil fuel combustion considered among the main causes. Scientists predict the continuous global warming to result in serious environmental and economic consequences on precipitation rates, droughts, growing crops, rivers' flow rates, ice melting, and sea-level rising. To meet these challenges, renewable energy sources such as solar photovoltaics are widely seen as clean alternatives. Recently, they have grown in both development and deployment. However, the economic feasibility, energy density, stable on-demand availability and technical challenges of integrating the intermittent renewable sources with standing power grids have long constituted key obstacles. Even so, innovation, mass-production, and government subsidies can interactively lead to the grid parity. Inventions with high technological and economic values are usually protected through patent filings. Since patents act as a bridge between successful innovative activities and markets, the study of their indicators is vital to understand the technical situation and to evaluate the subsidizing policies. Introducing an exclusive definition of the technological system of photovoltaics, this article aims to accurately identify the relevant patent applications and to analyse their trends geographically, organizationally and technically.

1. INTRODUCTION

Among the wide range of existing renewable energy sources, solar photovoltaics (PV) is considered as "the cleanest and safest technology with which to generate electricity even at the GW production scale" [1, p. 24]. Since the discovery of PV effect in the nineteenth century, the technology has experienced dramatic development vertically – in terms of solar cell types, technological generations and efficiencies [2, 3], horizontally – in terms of its associated technical fields in chemistry, physics, electronics, and mechanics [4, 1], as well as on the market dynamics level of production and deployment [5, 6, 7, 8].

Today, development of material components, manufacturing methods, and applications for both PV cell and balance of system (BoS) technologies is a substantial research field. Thousands of corresponding scientific articles as well as patent applications are being published yearly [9, 10, 7, 11]. Patents are widely considered as a bridge between successful research and development activities on the one hand, and commercial markets on the other. They are usually filed by companies, universities, and research institutes to protect intellectual properties of high technological and economic values. Accordingly, the study of patent indicators has been of central importance for researchers in both natural- and social sciences. While patents can offer chemists, physicists, and engineers a comprehensive picture of the current technological situation, the state of the art, and development prospects, they provide policy makers and economists with a rich data source to evaluate the effectiveness of innovation and subsidizing policies.

Patent databases contain information of millions of patent applications in almost all technological fields. Consequently, the accurate identification of patent filings relevant to a specific technology is not a simple matter. Such accurate identification is nonetheless crucial for ensuring the quality of patent indicators and the validity of conclusions drawn out of them. Even utilizing the technological classification systems developed by patent offices, the identification process is still confronted with numerous difficulties and challenges. First, the complexity of high-tech systems makes it challenging to distinguish between similar technologies without detailed technical verification. The second difficulty is related to the diversity of large technological systems, whose components usually belong to a wide range of different technologies. Third, it is difficult to address market-oriented research questions depending solely on technological classification. Pavitt [12, p. 95] highlighted the importance of effective matching between the established patent classification scheme, the industrial classifications, and technically coherent fields of development. Fourth, the subjectivity of the technological classification of patent filings due to patent examiner judgements is considered another hurdle for the identification and assignment process [13].

The purpose of this article is to provide a comprehensive definition of the technological system of photovoltaics in terms of its structure and components, to systematically identify its relevant patent applications, and to analyse their geographical, organizational, and technical trends. Furthermore, the article reviews the most influential PV patents over the past decades. Besides the comprehensive PV system review, the main contributions of the present article lay in the patent identification approach. Not only can the resulting patent classes' inventory be further used to address wide range of research questions regarding the PV sector, but also the identification methodology itself can be adopted for other technological sectors.

The article is organized in five sections. Section 2 outlines the structure, work principle, and various components of the PV technological system. Section 3 compares different identification methods of patent applications and introduces the research methodology, data sources, and indicators. In section 4, the results concerning the global development trends of the PV technological system are analysed. Finally, section 5 synthesises the main findings and draws conclusions.

2. THE TECHNOLOGICAL SYSTEM OF SOLAR PHOTOVOLTAICS

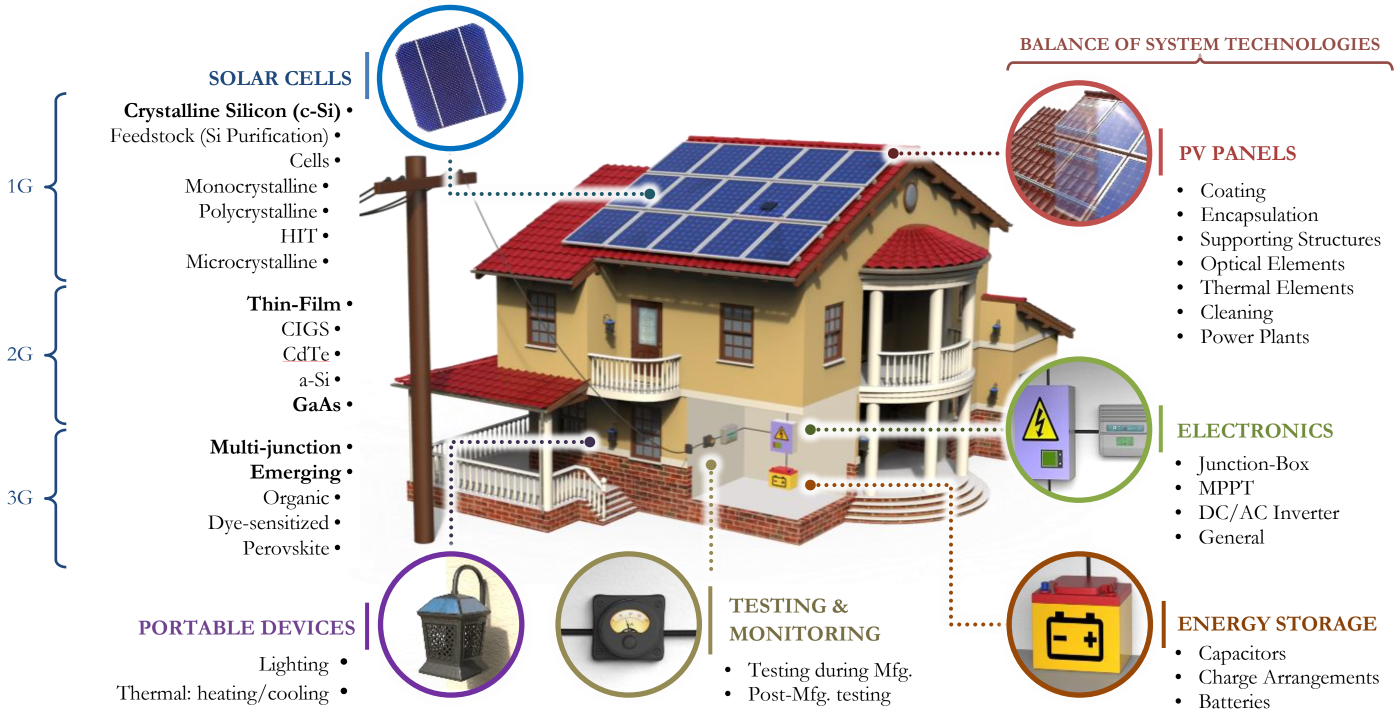
The PV technological system is a power system comprises a sequence of interconnected components that work together to convert sunlight energy into electricity, utilize the generated energy, store it, or invert it (figure 1). Accordingly, a PV system, whether centralized utility-scale or distributed, consists of two main groups of elements: solar cells, and balance of system technologies (BoS).

While cells are responsible for generating electric energy out of the solar irradiation, BoS components are important for connecting, chemically protecting, and mechanically mounting the cells into panels, as well as electronically regulating their output levels to be used, stored in batteries, or fed into the utility grid. Additionally, the system includes testing and monitoring processes and portable devices powered by PV electricity. (See figure 1 for an overview of the PV system components).

2.1 Solar Cell Technologies

Solar cells represent the building block and main component of PV systems. A solar cell is defined as an electrical device that directly converts the energy of photons into direct current (DC) electricity through a chemical/physical phenomenon called the photovoltaic effect. Photons with energy exceeding the cell material band-gap are absorbed causing excitation of charge-carriers and thus electric current and voltage. The conversion efficiency (η) is calculated as the percentage of the incident light power on the cell surface that is converted into electrical energy under standard conditions.

Figure 1: The Technological System of Solar Photovoltaics



Author's own elaboration

Solar cells are classified into three generations of technology. While the first generation (1G) encompasses crystalline silicon wafer-based cells, the second generation (2G) comprises thin-film technologies such as Cadmium telluride (CdTe), Copper indium gallium di-selenide (CIGS), amorphous Silicon (a-Si), and single-junction Gallium Arsenide (GaAs) cells. On the other hand, the third generation (3G) includes the emerging cell technologies of organic materials as well as the multi-junction cells.

Only c-Si and thin-film technologies are available in mass production for civil applications. In terms of market share, c-Si cells are dominant in the market with 93% of the total produced capacity in 2015 (69% multi-crystalline cells and 24% mono-crystalline), while thin-film technologies form only 7% of the total production (3% a-Si, 2.5% CdTe, and <2% CIGS) [14]. On the other hand, the expensive high-efficient technologies of GaAs and multi-junction cells are mostly used for space power applications [15, 16].

2.1.1 Crystalline Silicon Technologies (c-Si)

Single-junction c-Si is currently the dominant cell technology in the global PV market. The wafer-based conventional cells are classified according to their crystalline structure into four main types: Mono-crystalline, Poly-crystalline (i.e. multi-crystalline), Heterojunction with Intrinsic Thin layer (HIT), and Microcrystalline. Regardless of the final crystalline structure, the initial stage of c-Si cell manufacturing aims at the production of high-grade purified silicon. Raw materials of quartz sand (SiO_2) and coal (C) are processed inside electric arc oven to generate metallurgical-grade silicon (MG-Si 98% pure). MG-Si undergoes further hi-tech processes in several reactors to produce solar-grade polysilicon (SG-Si with at least 5 nines purity 99.999%) [3, 17, 18]. Such reactors include the fluidised bed reactor and the Siemens reactor: a common purification technology originally developed and protected in series of patent filings by the German company Siemens over the period 1954-1961.[1]

The second stage of manufacturing processes comprises crystal growth methods, where mono and multi-crystalline ingots are produced. While mono c-Si consists of a continuous single crystal, poly c-Si contains multiple small crystals. Consequently, they differ in their production processes. **Mono-crystalline** ingots can be obtained using the Czochralski process (Cz-Si),[2] float-zone,[3] or Bridgman–Stockbarger techniques (BST)[4] [19]. On the other hand, **poly c-Si** follows simpler manufacturing processes such as Bridgman columnar growth (BCG) and block-casting techniques.[5]

In the following manufacturing stages, both mono- and poly- ingots are sliced into wafers (with a typical thickness ~ 300 μm) to be doped with p-n impurities and soldered with conducting surfaces, which together compose the solar cell. Efficiency records for such PN homojunction-barrier type cells are 26.1% and 22.3% for mono- and poly- cells respectively [2].

A novel design modification to the standard silicon cell structure was introduced by the University of New South Wales in the late eighties [21]. **Passivated Emitter and Rear Cell (PERC)** is designed through adding a dielectric passivation layer to the bottom of a c-Si cell reducing the metal/semiconductor contact area [22]. Consequently, significant cell efficiency improvements are achieved through reducing electron recombination, increasing rear surface reflection, as well as reducing rear-layer heat absorption.

As indicated by its name, a **HIT cell** is obtained by subsequently depositing p- and n-type hydrogenated amorphous silicon (a-Si:H) thin layers (~ 20 nm each) on the top and bottom sides of an intrinsic c-Si wafer (~ 200 μm) [23]. Such hybrid structure of conventional and thin-film technologies was originally developed and patented by the Japanese company Sanyo in 1990 [24, 25].[6] With the advantages of high conversion efficiency (research cell record at 26.6%), improved temperature coefficient, higher open-circuit voltage, and less needed energy during manufacturing, HIT cells are considered as a promising technology.

The fourth type of c-Si technologies is **microcrystalline**. Being a form of porous silicon, microcrystalline silicon (sometimes referred to as Nano-crystalline) has tiny grains of c-Si within its amorphous phase. It is considered as thin-film c-Si technology with efficiency record of 21.2%. Unlike the other c-Si technologies (which are based on self-supporting wafers), the active microcrystalline thin layer (~ 1 μm) is deposited[7] from a gas-phase (SiH_4 and H_2) through

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[1] For technical details, check the patent filings of EPODOC numbers DE1954S039578, DE1958S058066, and US19610090291 [91].

[2] In Cz-Si, a seed crystal is submerged into rotating melted polysilicon, then gradually dragged allowing for fluid silicon to crystallize thereon.

[3] In float-zone method, an induction heating coil is gradually drawn from the side of a seed crystal vertically towards a polysilicon bar allowing for melted silicon in the induction zone to feed the crystal.

[4] In BST, heated liquid polysilicon is slowly cooled from the direction of a seed crystal allowing it to grow.

[5] In BCG, melted polysilicon undergoes gradual directed cooling process allowing for small mono-crystals to form and vertically grow [20].

[6] For technical details, check the patent filing of EPODOC number US19910757250 [25].

[7] With CVD, thin solid films are formed on a substrate surface through the reaction of gas precursors in vacuum.

plasma enhanced chemical vapour deposition (PECVD)[8] or hot-wire chemical vapour deposition (HWCVD)[9] processes [26, 27] on a glass substrate before treated into PIN structure.

2.1.2 Thin-film Technologies

To avoid the high economic and environmental cost of c-Si cells (in terms of material and energy) [28], a second generation of technology has been introduced since 1970s. Thin-film PV cells are manufactured by depositing thin layers of photovoltaic materials (thickness < 2 μm) to form a heterojunction barrier. Due to the direct and wide bandgap of most thin-film semiconductor materials (1.5-1.8 eV), 2G cells have better temperature coefficients as well as a good performance in indirect light. Furthermore, the main advantage of thin-film cells stems from their very small thickness. Accordingly, they can be deposited on flexible substrate materials, they can be connected into modules during the manufacturing process of the cells through laser cutting, and they can be vertically stacked to form the 3G tandem (multi-junction) cells (see section 2.1.4).

The categorization of thin-film cells is based on the deposited materials [29]. This includes II-VI compound semiconductors such as Cadmium telluride (CdTe) and Cadmium sulphide (CdS); I-III-VI semiconductors such as CIGS; and amorphous silicon (a-Si). **CdTe films** can be produced using various techniques such as sputtering, high vacuum evaporation (HVE), and metalorganic chemical vapour deposition (MOCVD)[10] [30]. Its cell efficiency record is 22.1%. On the other hand, **CIGS cell technology** with efficiency record of 22.9% can be manufactured using screen-printing, spray coating, spin coating, MOCVD, or electron beam deposition [31, 32].

a-Si thin-films with PIN structure are usually obtained using PECVD manufacturing process similar to microcrystalline silicon. However, the main difference between a-Si and c-Si technologies is the order of Si atoms. In a-Si material, atoms have extremely irregular structure with many dangling bonds, which are passivated with hydrogen atoms during deposition to mitigate electron-hole recombination. a-Si thin-film cells (~ 0.5 μm thickness) have an efficiency record of 14% and are widely used to power small electronic devices such as calculators.

The disadvantages of the discussed 2G thin-film technologies include their slightly lower efficiencies compared to c-Si, GaAs and multi-junction cells; the scarcity of raw Tellurium; the toxicity of Cadmium; and the degradation of a-Si power efficiency under light influence due to Staebler-Wronski effect [33, 34].

2.1.3 Single-junction Gallium Arsenide (GaAs)

Despite being a type of thin-film technologies, the III-V direct bandgap semiconductor GaAs has superior electronic properties. Therefore, it is classified as a separate group in the present

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[8] In PECVD, a plasma created by AC between two electrodes is used to enhance the chemical reaction of the gas precursors in CVD.

[9] In HWCVD, gas precursors are decomposed on heated filament's surface to form radicals before being deposited on a heated substrate.

[10] In MOCVD, precursor gases are combined at high temperatures in a reactor to undergo a chemical reaction, which results in depositing thin-film layers of the product on a substrate.

definition of the PV system. This is also consistent with the NREL classification of PV cell technologies [2]. With its bandgap level of 1.424 eV (at 300 K), GaAs is considered the optimum material to match the distribution of photons in the solar spectrum. Accordingly, it holds the highest efficiency record for a single-junction solar cell of 29.1%. This wide bandgap also yields a good performance under low light conditions. Besides its high saturated-carrier-velocity, GaAs has a low temperature coefficient, making it suitable for hot regions, as its conversion efficiency is less sensitive to temperature. Additionally, GaAs films are lightweight, impervious to radiation and ultra-violet light, and thus convenient for aerospace applications. The main disadvantage of GaAs cells are their very expensive prices comparing to silicon-based cells.

Several processes can be used to manufacture GaAs cells. Single crystals of GaAs are usually grown using the vertical gradient freeze (VGF) method [35], the Bridgman-Stockbarger technique (BST), or the liquid encapsulated Czochralski (LEC) growth process[11] [36, 37]. Alternatively, GaAs layers can be deposited using MOCVD process [38].

2.1.4 Multi-junction Cells

To circumvent the Shockley-Queisser limit for single-bandgap devices (efficiency ≤ 31% or 41% depending on concentration ratio) [39], a third generation of solar cells has been developed since 1979 [40, 41]. The principle of this technology is to stack multiple thin-film layers of photovoltaic materials with different bandgaps to absorb the larger possible portion of the solar spectrum (sunlight wavelengths) [42]. Such semiconducting p-n layers include Ge, GaInAs, GaInP, GaAs, InAlAs, a-SiGe, μSi, and a-Si:H. Consequently, the resulted multi-junction cells can achieve very high conversion efficiencies [43] (current record is 46% under concentrator system). Because of their complex manufacturing processes and high price, multi-junction cells are not used in civil applications but rather for powering spacecraft and satellites such as the International Space Station, Mars Global Surveyor, Juno Spacecraft, and Hubble Space Telescope.

2.1.5 Emerging Technologies

The fifth family of solar cells is the emerging technologies. It includes three main groups that are still non-commercial (under research and development phase): Organic, Perovskites, and Dye-sensitized solar cells (DSSC).

Being developed since the late 1980s, **Organic solar cells** use conductive organic polymers (such as copper-phthalocyanine and perylene tetracarboxylic derivative) to absorb light energy and generate electricity [44]. Organic light absorber layers (i.e. active layers) are very thin (100-200 nm) consisting mostly of carbon. Consequently, lightweight flexible organic modules can be fabricated using roll-to-roll manufacturing techniques [45]. The cell efficiency record of organic technologies is 15.6%. Despite their low efficiency, organic materials are of relatively low cost and can offer the advantage of transparent solar cells [46, 47, 48]. Unlike inorganic semiconductor cells that generate electrons and holes, organic cells are considered excitonic

[11] In LEC, the elementary materials encapsulated in a boric oxide are placed inside a high pressure growth chamber and heated up before a rotating seed crystal is immersed therein and gradually pulled allowing the single crystal to grow.

solar cells, where incident photons generate tightly bound Frenkel excitons first, before being separated with the use of a bulk heterojunction of mixed donor and acceptor layers that transfers and receives electrons respectively [49].

On the other hand, **DSSC** was originally developed by Brian O'Regan and Michael Grätzel in 1991 as a promising low-cost PV technology [50, 51]. The invention was protected with several patent filings over 1991-1993.[12] DSSCs consist of nanostructured metal-oxide electrodes (such as nanocrystalline/ nanoporous TiO_2) covered with sensitizing dyes (e.g. Ruthenium-polypyridine) and liquid iodide/triiodide electrolytes [52, 53]. When photons hit the dye, they can release electrons from their conjugated bonds to form electric current out from the anode through the outer circuit and back to the platinum cathode to be internally carried back to the dye through the electrolyte. The photo-electrochemical system of DSSC is fabricated using roll-printing techniques. With a conversion efficiency record of 11.9%, DSSC offers cheap, flexible and semi-transparent cells. However, the major disadvantages of this technology are related to the use of liquid electrolytes, which are vulnerable to leakage, expanding, or freezing under extraordinary temperature conditions. Accordingly, solid-state DSSC can form a promising upgrade of the technology.

Being introduced in 2009 [54], the use of a **Perovskite** material (crystal structure of ABX_3) as light absorber in solar cells has shown promising high efficiency and charge carrier conductivity. Within only few years, the technology has witnessed a significant efficiency improvement from 3.8% in 2009 to 24.2% in 2019. Furthermore, Perovskite/Silicon Tandem cells achieved an efficiency record of 28% in 2019 [2]. Perovskite solar cells typically depend on hybrid organic-inorganic lead halide-based materials as their active layer (thickness ≈400 nm) [55]. Having a similar structure to DSSCs, Perovskite cells offers low production cost and relatively simple manufacturing processes (i.e. spin coating, screen printing, or vapour deposition techniques). However, incorporating lead and being sensitive to high temperature, moisture and oxygen, are widely considered as stability obstacles against the Perovskite cell technology [55].

The solar PV cell technologies discussed in this section are comprehensively summarized in Table 1. It contains information about the material bandgap, existing options of manufacturing process, laboratory cell-efficiency records and their holders based on [2], as well as the market share and practical applications of each technology.

[12] For further technical details, check the patent filings of EPODOC numbers DE19924207659 and US19930140098 [92].

Table 1: Overview of Solar PV Cell Technologies

PV Cell Technology	Band-gap [eV]	Manufacturing Processes	Efficiency Record [%]	Record Holder/Yr. [Country]	Market Share	Applications
Crystalline Silicon						***Civil Applications*** *(e.g. devices, residential, commercial, and utility-scale power plants)*
Mono-crystalline	1.11	Cz-Si, float-zone, BST	27.6 (26.1)*	Amonix/2005 [US] (ISFH/2018 [DE])	24%	
Poly-crystalline	1.11	BCG, block-casting	22.3	FhG-ISE/2017 [DE]	69%	
HIT	1.11	Deposition	26.6	Kaneka/2016 [JP]	<1%	
Micro	1.11	PECVD, HWCVD	21.2	Solexel/2014 [US]		
Thin-film						
CIGS	1.7	scr.-print, coat, MOCVD	23.3 (22.9)*	NREL/2014 [US] (Solar Frontier/2018 [JP])	<2%	
CdTe	1.5	sputter., HVE, MOCVD	22.1	First Solar/2015 [US]	3%	
Amorphous Si:H	1.5-1.8	PECVD	14	AIST/2016 [JP]	3%	
GaAs	1.42	VGF, BST, LEC, MOCVD	30.5 (29.1)*	NREL/2018 [US] (Alta-devices/2019 [HK])	Non-cml.	***Spacecraft Applications***
Multi-junction	multiple	MOCVD, mech.-stacking	46	FhG-ISE|Soitec/2015 [DE|FR]		
Emerging						***Research*** *(still under development)*
Organic	1-4	Roll-to-roll mfg.	15.6	SCUT-CSU/2018 [CN]		
Dye-sensitized	≈3.2	Roll-printing	11.9	Sharp/2012 [JP]		
Perovskite	≈1.5	spin-coat, scr.-print, VD	28 (24.2)*	Oxford PV/2019 [UK] (KRICT-MIT/2019 [KR-US])		

*. Efficiency values between parentheses are for non-concentrator systems. Author own elaboration.

2.1.6 Common Elements

Regardless of the semiconductor materials used in fabricating PV cells, there are several common elements, components, and techniques relevant for almost all cell technologies. These are (1) the materials and deposition processes of cell electrodes, (2) the texturing (roughening) methods of cell surfaces using acid etchants to reduce optical losses due to internal reflections, (3) wiring and inter-cell connection techniques within solar modules, and finally (4) doping materials and methods for producing the p- and n- semiconductors of cell junctions.

2.2 Balance of System Technologies

While cell technologies focus on the physical and chemical principles of converting light energy into electricity at a single-cell level, the balance of system technologies are related with delivering the generated energy in a sufficient manner to be used in the consumption side [13]. This includes the production and installation of solar panels (e.g. building integrated photovoltaic systems and thermal arrangement [56]), electronic charge controllers (e.g. maximum power tracking systems [57]), battery storage units [58], testing and monitoring methods [59, 60], and solar-powered portable devices.

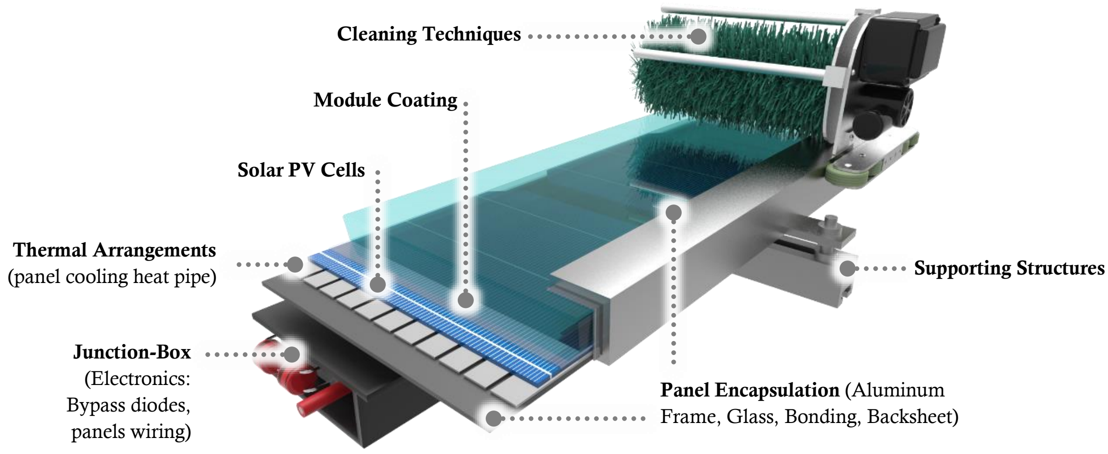
2.2.1 Solar Panels

Solar panels are produced by coating, wiring, and encapsulating arrays of PV cells together. PV cells can be connected in series to increase output voltage, or in parallel to increase current. With the growing demand for solar energy powering both residential and utility-scale plants, the development of panel mounting and racking systems has gained a growing importance.

The technological group of solar panels (figure 2) concerns mainly with mechanical engineering techniques. It consists of seven subgroups: (1) coating and protection processes of solar cell surface, (2) design of panel containers and encapsulation techniques, (3) roof covering methods and the mechanical design of mounting, supporting structures, and sun tracking systems [61], (4) optical elements and arrangements such as mirrors and lenses used in concentrator PV systems (CPV) [62],[13] (5) thermal elements and arrangements mainly designed for cooling solar cells in order to avoid efficiency degrading due to high temperatures, (6) cleaning methods of PV panels including sand, dust, and snow removing robots and techniques, and finally (7) any technological aspects related to designing, building and controlling utility-scale PV power plants.

[13] CPV systems use lenses and curved mirrors to concentrate sunlight onto PV cells in order to multiply the solar intensity (can exceed 1000 suns). With cooling systems and multijunction cells, CPV has achieved very high conversion efficiency (up to 46%) [2].

Figure 2: Solar Panel Components



Author's own elaboration

2.2.2 Electronics

The electronic circuits relevant to PV technology include three main groups: junction boxes, charge controllers, and inverters.

Junction boxes are installed on the backside of each solar panel (figure 2). They contain diodes and cables wiring panels together and with inverters or batteries. Two types Schottky-barrier diodes are used to protect panels from being overheated or damaged by reverse current: bypass-diodes and blocking-diodes. During daytime, if a panel get shaded, its current output falls drastically, so is the current through the string of the series panels to which it belongs as well as the output power. Additionally, the unshaded panels produce higher voltages that can reverse-bias the shaded cells causing hot-spot heating. Bypass diodes wired in parallel with each panel are used to circumvent this effect. On the other hand, blocking diodes connected in series between PV panels and batteries guarantee that electric current flows only in the direction from panels to batteries. Consequently, they protect the panels from current flow from the batteries at night.

Charge controllers are used to regulate power transfer from PV panels to batteries in off-grid systems. They protect batteries from overcharging, and guarantee the operation of the solar panels at their peak power using maximum power point tracking algorithms (MPPT) that adjust the impedance connected to the panels depending on the operational conditions of illumination and temperature. There is a wide range of MPPT algorithms such as: perturb and observe, incremental conductance, hill-climbing, as well as fuzzy logic control and artificial neural network algorithms [63]. Implementing an MPPT system can yield 20% power gain.

To match the generated PV power with the utility grid for feeding-in purposes, the direct current (DC) output of PV panels needs to be inverted into alternating current (AC). **PV inverters** are used for this purpose. They are also useful in the local off-grid network to provide electrical appliances with their rating AC input levels.

2.2.3 Energy Storage

PV power generation is mainly dependent on sunlight intensity, which variates during the day as well as throughout the year. Accordingly, it is essential to PV systems to have specific means and components that guarantee the availability of energy whenever it is needed at the consumption side. The balance between energy supply and consumption is achieved using energy storage systems. This technological group contains the means and techniques for storing the PV generated energy, either internally (in-cell storage) using capacitors for short-term storage, or externally using batteries for long-term storage. Energy storage is an important feature especially for off-grid PV systems.

2.2.4 Testing and Monitoring

This group includes the inspecting techniques for accuracy and completeness of the industrial processes implemented during the manufacturing of PV system components. Furthermore, it comprises physical, chemical and electrical methods for testing the quality and performance of final PV products (i.e. solar cells, panels, and PV power plants). Accordingly, such monitoring techniques are classified into two categories: during-manufacturing, and post-manufacturing testing methods.

2.2.5 Portable Devices

The last group in the present definition of PV technological system comprises the portable devices powered by solar modules. Such devices represent complete systems of solar cells combined into panels and connected to electronic circuits and batteries for electrical energy storage. Such energy is meant to be used for daily life applications. The complete systems are packaged as integrated devices. This includes lighting devices (e.g. street-lamp systems, searchlights, luminaires, etc.), as well as thermal devices for heating or cooling purposes.

3. DATA AND METHODOLOGY

For the empirical analysis introduced in this article, patent data from the Worldwide Patent Statistical Database (PATSTAT) version 2016b were mainly used. PATSTAT contains more than 68 million patent applications filed worldwide, over more than two hundred years, and covering all patentable subjects, fields, and technologies. Additionally, for the technical analysis of the most influential patent applications, full patent documents were collected using the patent search engines: European Patent Office (EPO) Espacenet, Google Patents, as well as the web portals of some domestic patent authorities, i.e. the German patent office (DPMA), the United States Patent and Trademark Office (USPTO), and the Japan Patent Office (JPO).

This section discusses the use of patents as an indicator of technological change that can lead to economic growth. It further introduces patent families, quantity and quality indicators, and classification systems. After that, it reviews the state-of-the-art approaches used for identifying patent applications relevant to a specific industry. Finally, the author’s identification approach for PV patents is introduced.

3.1 Patent indicators

With more than one million new inventions being yearly filed in patent documents, patents are considered among the richest information sources of technological innovation. They reflect the accumulation of inventiveness knowledge and innovative activities conducted by research and development laboratories. Patenting systems were originally created as legal protection instruments that give inventors exclusive time-limited rights (20-years) to commercially produce, use, and sell their inventions while preventing others from making any commercial use out of them without a prior permission or licence. Therefore, they are widely seen as a form of intellectual property rights that encompass high technological and economic value [64]. Patents comprise an interesting detailed insight on the accumulated knowledge of human beings for a relatively long period of time, along with the state-of-the-art in various cognitive fields. Additionally, being disclosed to the public containing detailed technical information and metadata regarding citations (knowledge sources) and affiliations (geographical locations) of applicants and inventors, patent indicators are increasingly used by researchers in both engineering and economics of innovation studies.

Nevertheless, the use of patent data as a sole measure of innovation encounters some limitations. Besides the wide variation in patenting propensity across countries, sectors, and organizations [65], intellectual property laws and administrative procedures vary widely across patent authorities of different countries, and are subject to continuous adjustments. This fact needs to be taken into consideration especially when comparing absolute counts of patent filings across countries. Moreover, the cognitive values of patents are not alike; some patents contain radical innovations of high value, while many others have modest incremental improvements. In general, patents are directly related to solving technical problems, developing new processes, or discovering new materials, ideas, or inventions. However, they have nothing yet to do with products and markets. Therefore, they cover the inventiveness stage of technological change, rather than the entire innovative performance.

3.1.1 Patent Families and Priority Filings

A patent family is defined as a group of patent applications filed in several countries (patent authorities) to protect the same invention [66]. Families are usually used in patent statistics to avoid double counting of same inventions when considering cross-country analysis. Among different procedural definitions of patent families, the definition used in the present analysis is the priority-filings. As an extended family definition, a **priority filing** [67] uses the earliest patent application of each invention to indicate its family regardless of patent authority. It hence gives an accurate indication of the time and place where inventions first took place. Accordingly, priority filings can be used to capture and compare the complete landscape of patenting activities of several inventor countries. In the present analysis, the fractional counts of priority filings are used as a patent quantity indicator.

3.1.2 Transnational Patents and International Potential

Inventions with high economic and technological values are usually protected through patent applications enforceable in several markets across countries' national borders. Such patent applications are referred to as transnational patents. Technically, **transnational patents** can be defined as patent applications filed at the European Patent Office (EPO),[14] and international patent applications filed under the Patent Cooperation Treaty (PCT),[15] avoiding double counting of patents from the same family (Equation 1).

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[14] The European Patent Office was formed in 1977. Before this date, no EPO patents were filed.

[15] The Patent Cooperation Treaty was signed in 1970 and has been effective since the 24th of January 1978. Before this date, no PCT patents were filed.

$$\boldsymbol{TN = \{x \mid x \in EPO \cup PCT\}} \qquad \text{(Equation 1)}$$

To proximate the business potential of patent applications from an international perspective, the percentage share of patent families that contains at least one transnational patent application is calculated at the state level[16] using Equation 2. Referred to as the **International Business Potential (IBP)**, the calculated share is used as a patent quality indicator.

$$\boldsymbol{IBP = \frac{TN}{Prio} \times 100\%} \qquad \text{(Equation 2)}$$

Where (for each country): TN represents the number of patent families that contains at least one transnational patent application (EPO or PCT). Prio represents the total number of the country's priority filings. Both TN and Prio are calculated on a fractional count basis.

3.1.3 Patent Impact Factor

As a second quality indicator, a patent impact factor (PIF) based on forward citations is calculated for the purpose of identifying the most influential PV patents. The PIF is calculated for each patent application (*i*) as the number of citations received at family level (*C*) over the priority patent life time (*age*),[17] as mathematically expressed in Equation 3.

$$\boldsymbol{PIF = \frac{C_i}{age_i}} \qquad \text{(Equation 3)}$$

3.1.4 Patent Classification

During examining processes, patent applications are classified into groups based on their technological content in order to facilitate novelty establishment, testing, and comparison with the state-of-the-art. This process implements pre-defined classification systems agreed among patent offices and examiners. The **International Patent Classification** (IPC) is considered the most common system. It is used by more than hundred patent offices worldwide. Developed by the World Intellectual Property Organization (WIPO) under the Strasbourg Agreement 1971 and being updated on a regular basis, IPC provides a hierarchical system of symbols for the classification of patents according to the different areas of technology to which they pertain. In its 2016.01 version, the IPC divided the universe of patentable technologies into 8 main areas (named sections). Under which, detailed levels of 130 classes, 639 subclasses, 7,434 groups, and 65,152 subgroups were introduced to provide the full classification at its fifth level (Figure 3). This detailed allocation allows for the subject matter of a patent to be thoroughly classified.

[16] The assignment of patents into countries is done based on the location of inventors.

[17] The division of patent forward citations over patent age in the PIF is done to guarantee an equitable basis to compare patent applications that were filed across long period of time.

Figure 3: International Patent Classification System

SECTION H: Electricity

CLASS H01: Basic electric elements

SUBCLASS H01L: Semiconductor devices…

GROUP H01L 31: sensitive to infra-red radiation, light, electromagnetic radiation…

SUBGROUP H01L 31/052: Cooling means directly associated with the PV cell…

H 01 L 31/052

Data source: WIPO IPC version 2016.01. Author's own elaboration

3.1.5 Technological Specialization

To capture the relative technological specialization of a country in patenting activities, the ***Revealed Technology Advantage (RTA) index*** is used [68, 69]. RTA is calculated as the ratio between two shares (Equation 4). The nominator is the share of a country's patent applications in a specific technological field over its total patents. The denominator is the share of the worldwide patents in the field over the worldwide patents in all fields.

$$RTA = \frac{P_{ij}/P_{iT}}{P_{Nj}/P_{NT}} \quad \text{(Equation 4)}$$

- *P*: is the number of Patent applications,
- *i*; represents the inventor country under consideration,
- *N*: represents all inventor countries,
- *j*: represents the technological field under consideration,
- *T*: represents all technological fields.

Accordingly, an RTA value > 1 indicates that the country has a relative advantage in the technological field compared to other countries. In other words, it means that the concentration of patenting activities by the country in the field j is larger than the world average. On the other hand, an RTA < 1 means the opposite.

3.1.6 Sectoral Identification of Patents

The accurate identification of patent applications that are relevant to a specific industrial or technological sector is a vital prerequisite for any sectoral patent analysis. Accordingly, several approaches can be found in the scientific literature for this purpose. Such approaches are: patent classification systems, keyword search, topic modelling and machine learning methods, industrial-based identification, and expert selection. Using any of these approaches is a trade-off between data completeness, relevancy, and method replicability. This section introduces a brief review of these approaches, their strengths, weaknesses and applications.

1. Patent Classification Search

Following this approach, patent filings relevant to a specific technology are retrieved using the patent technological classes (assigned by patent offices during examining process) or their overlaps [65, 70, 71]. Such classification systems are IPC (international), UPC (American), ECLA (European), and CPC (Cooperative- jointly developed by the European and American patent offices). The most famous example of this approach for environmental innovation research is the WIPO IPC Green Inventory (IGI).

Besides their replicability, direct availability, and technological basis, a key advantage of using patent classes is their language-independent nature. Searching patent documents written in different languages can be simply obtained through filtering IPC codes. This advantage is more pronounced in compared with other approaches such as keywords, topic-modelling, or expert-selection, where translating from different languages is essential for inclusiveness.

On the other hand, the IPC searching approach is not directly applicable if the designated sectors mismatch its classes. Hence, it is possible to obtain noisy inaccurate results when considering market-oriented research questions. Besides its dynamic nature (being regularly updated through adding/removing classes), classifications can be subjective due to examiners' judgement.

2. Keyword Search

In this approach a predefined set of keywords (technical terminology) is used along with Boolean rules (AND, OR, NOT, etc.) to search the important segments of patent applications (titles, abstracts, claims, etc.) and select the relevant patents [72, 73]. Keywords can be either proposed by industrial experts and engineers, or extracted from representative patent filings.

Although keywords are among the most popular and convenient methods for technology-based patent analysis [74, 65], it has some drawbacks when applied alone. Besides being time consuming, some relevant patents can be falsely excluded because of the various ways a technology can be described in the patent text which sometimes do not include the exact keywords. On the other hand, the keywords can be mentioned in the context of a non-relevant patent for explanation, exclusion, or comparison purposes. Accordingly, mere keyword searching might end up with many false positives. Furthermore, the outcome of this approach can largely differ when using different keywords or even when changing the combinational logic rules.

3. Topic Modelling

Topic modelling and machine learning methods are mainly based on the use of computer for recognizing patterns in patent texts. Such patterns can then be used for identifying specific technologies automatically after being trained with a sufficient amount of data [13, 75]. Although these methods sound very promising, the large effort, time and computational power they need in the machine teaching stages as well as the difficulty to find the exact point when the machine can be considered well-trained, and thus can be further used for automatic classification, are all among the major drawbacks. Additionally, being very specific to its design circumstances and algorithm variables, the replicability of such methods is still questionable.

4. Industrial-based Identification

This approach starts with listing the active companies within the industrial sector under consideration. The next step is to search for patents filed by these companies. Applying such a firm-oriented approach can give precise results in terms of relevancy. However, some important data will be completely lost: especially for inventions by non-firm actors such as universities, research institutes, and individuals, or relevant innovations by firms from other industrial sectors. The second disadvantage is the need for additional data sources for firm activities and industrial sectors. Furthermore, some large companies might have a wide range of technological activities that can lead to false positives when including all their patent portfolios through this approach.

5. Expert selection of patents

In this approach, the relevant patents out of a pre-filtered stack of files are manually identified and classified into industrial sectors by a team of experts in different technological fields [76]. Although it is theoretically the most precise identification method, it is impractical and inapplicable when considering several thousands of patent applications.

All in all, combinations of these five approaches are increasingly being used in research to optimize the completeness, relevance, and replicability of patent identification. Such strategies can be found, for example, in [74, 77, 78] as well as in this contribution.

3.2 Methodological Approach:

In order to identify the patent applications related to the PV technological system, this paper introduces an integrated methodology that combines all the previously mentioned approaches. The main aim is to compensate the weaknesses of each approach with the strengths of the others, so that the final result can offer high levels of data completeness, relevancy, and replicability. The proposed methodology (figure 4) consists of four successive processes:

3.2.1 Building IPC inventory for PV system

PV-related IPC codes were extracted from four main types of sources: (1) the IGI, (2) energy and world patent reports published by the international organizations WIPO and OECD, (3) scientific publications, and (4) a general keyword search for IPC subgroups that refers to solar PV in their documentation.

This process resulted in a total number of 284 IPC subgroups being collected in a preliminary IPC inventory for the PV technological system.

3.2.2 Verification

The second process within the proposed approach is to verify the IPC codes collected in the preliminary inventory. Verification is defined as the internal checks that guarantee the system compliance with regulations, specifications, or imposed conditions [79]. Accordingly, the verification process of IPC codes checks whether they are originally designed for PV purpose or not. A thorough investigation of the technical terms and notes available in the IPC documentation were done for each subgroup individually.[18] Consequently, additional 38 IPC subgroups were added to the preliminary inventory, mostly belonging to a subclass that was introduced since 2014, and hence not included in the IGI and the reviewed literature. On the other hand, 99 IPC codes were excluded from the inventory in this stage, based on expert investigation, as they are irrelevant to PV. For example, many of the codes belonging to the

[18] For this process, three experts were engaged (a postdoc and two postgraduate researchers in engineering). Additionally, the final classification results were reviewed by two further experts (a physicist and a patent expert economist), and discussed in a scientific colloquium on energy and semiconductor research.

IPC group (H01L 21) were excluded, as they refer to the manufacturing of other electronic devices such as diodes, transistors, computer memories and integrated circuits. Such electronic devices undergo very similar manufacturing processes to those of c-Si cells. However, as the IPC clearly distinguish between the different final products, they were excluded from the inventory.

3.2.3 Validation

Validation is defined in engineering project management standards as an external checking process guarantees that the system meets the needs of the stakeholders [79]. Accordingly, the validation process here refers to the formal checks done to assure that the collected IPC codes in the inventory are actually used by examiners in patent offices around the world for classifying PV patents. This was done using text statistical analysis (keyword frequency check) across the titles of all patents classified under each IPC subgroup. PATSTAT database was used for this purpose. It resulted in excluding further 67 IPC codes that were figured out been used in practice for classifying patent applications related to CMOS camera sensors, transistors, and LCD technologies, and not related to PV cells or any other components within the PV technological system.

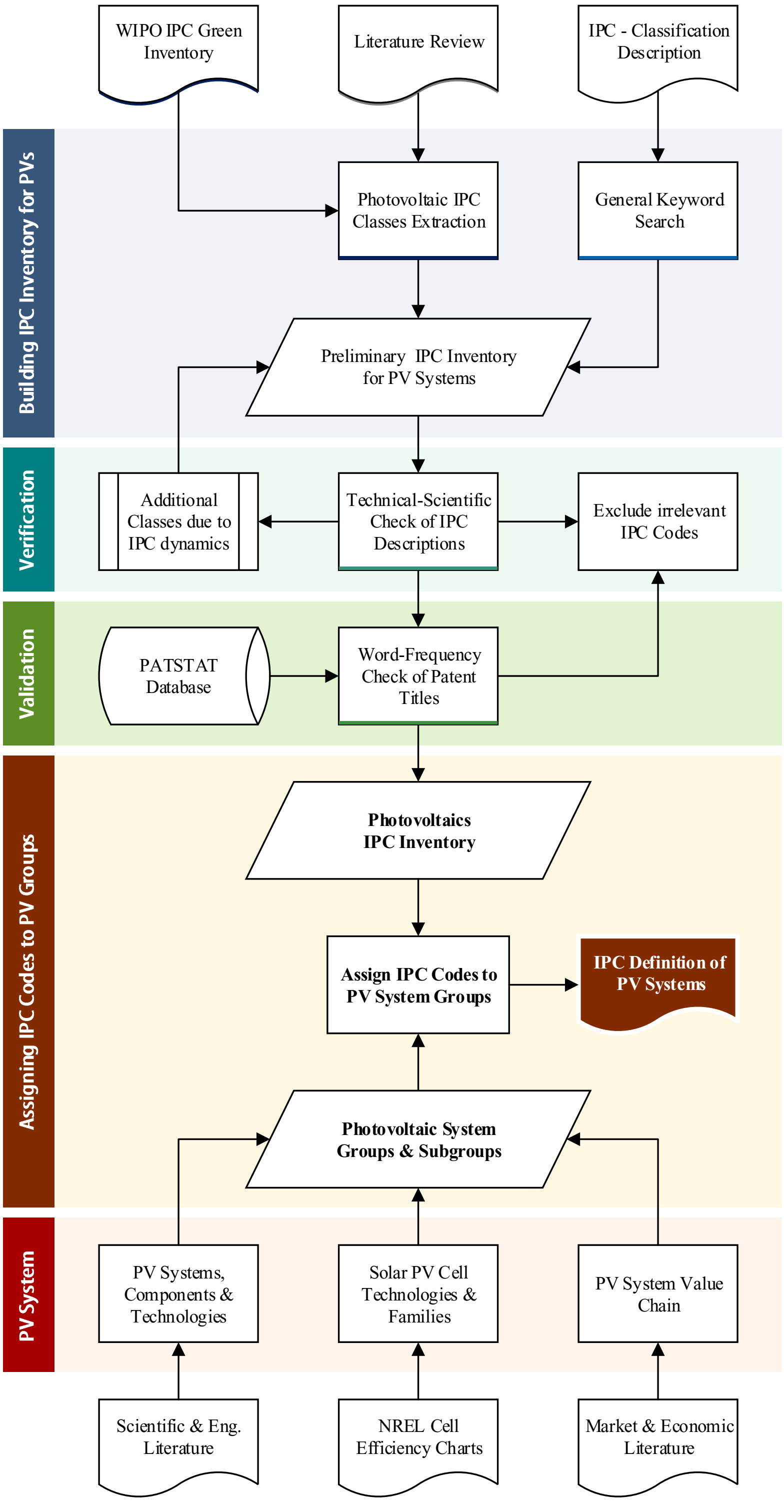
Up to this point, a final IPC inventory of 156 codes for PV technological system has been generated, undertaken multilevel examination checks, and thus ready to be used.

3.2.4 Assigning IPC codes to PV system groups

The final step in the proposed approach is the assignment of IPC codes into the PV system groups and components defined in section 2. However, two special cases were found: the ‘global’ and ‘combined’ subgroups. **Combined subgroups** contain patents related to several PV technologies at the same time. On the other hand, **global subgroups** are those not solely designed for PV technologies. They include patents for manufacturing processes or apparatus that represent an input for many technologies including but not limited to PV (e.g. the process of purifying silicon into single crystalline wafers is a global input process in the engineering world of Nano- and Micro- technology. Such wafers can be used for manufacturing transistors, integrated circuits, CMOS camera image-sensors, or mono c-Si PV cells). The significance of having the global IPC classes flagged in this definition is to indicate components in the PV system supply-chain that are not solely focusing on PV, but also supply other industries with elementary materials.

The final results of the introduced approach are shown in table 2, where the IPC codes (identified in this section) are assigned to the PV technologies (defined in section 2).

Figure 4: Research Methodology Flowchart



Author's own elaboration

Table 2: IPC Codes of the PV Technological System Components

GROUPS	SUBGROUPS	IPC CODES	
Cells	**1. Crystalline Silicon Cells**	H01L 31/028 H01L 31/0352**	H01L 31/068 H01L 31/18**
	1.1 Monocrystalline (Single Crystal)	C01B 33/02* C30B 29/06* C30B 15/00-36*	H01L 31/061 H01L 31/077
	1.2 Polycrystalline	C30B 28/00-14*	H01L 31/0368
	1.3 Silicon Hetero-structures (HIT)	H01L 31/0747	
	1.4 Thin-film Silicon Microcrystalline	H01L 31/06**	H01L 31/072**
	2. Thin-film Technologies	H01L 27/142 H01L 31/0445 H01L 31/046 H01L 31/0256**	H01L 31/0475 H01L 31/065 H01L 31/0248**
	2.1 CIGS, CZTSSe	H01L 31/032	H01L 31/0749
	2.2 CdTe	H01L 31/0296 H01L 31/0264**	H01L 31/073
	Both 4.1 and 4.2	H01L 31/0272	H01L 31/0336
	2.3 Amorphous Si:H	C23C 14/14* C23C 16/24* H01L 31/0376 H01L 31/04**	H01L 31/0392 H01L 31/075 H01L 31/20 H01L 31/07**
	3. GaAs Cells	H01L 31/0304 H01L 31/0693	H01L 31/0735
	4. Multi-junction Cells	H01L 31/0312 H01L 31/0328 H01L 31/043 H01L 31/047 H01L 31/0687	H01L 31/0725 H01L 31/074-0745 H01L 31/076 H01L 31/078
	5. Emerging Photovoltaics		
	5.1 Dye-sensitized Cells	H01G 9/20	
	5.2 Organic Cells	H01L 27/30 H01L 31/0384	H01L 31/0468**
	5.3 Perovskite Cells	H01L 51/42-48	
	6. Common Elements	H01L 31/036	
	6.1 Electrodes	H01L 31/0224	
	6.2 Surface Textures	H01L 31/0236	
	6.3 Cells Connection	H01L31/0463-0465	H01L 31/05
	6.4 Doping Materials	H01L 31/0288	
Panels	**1. Coating/Protection**	H01L 31/0216	H01L 31/041
	2. Containers/Encapsulation	H01L 25/00 H01L 25/16-18* H01L 31/02	H01L 31/0203 H01L 31/048-049
	3. Roof Covering and Supporting Structures	E04D 1/30 E04D 13/18 H01L 31/042	H02S 20/00-32 H02S 30/00-20
	4. Optical Elements/Arrangements	H01L 31/0232 H01L 31/054-56	H02S 40/20-22
	5. Thermal Elements/Arrangements	H01L 31/024	H01L 31/052-0525
	6. Cleaning	H02S 40/10-12	
	7. Power Plants	H02S 10/00-40	
Electronics	**1. Junction Box (Bypass Diodes)**	H01L 31/044-0443	H02S 40/34-36
	2. MPPT	G05F 1/67	
	3. Inverters, Feeding Circuit	H02J 3/38	H02S 40/32
	4. General Electronic Elements	H02S 40/30	
Energy Storage	**1. In-cell Storage (Capacitors)**	H01L 31/053	
	2. Battery Charging Arrangements	H02J 7/35	
	3. Batteries	H02S 40/38	
Monitoring/ Testing	**1.Testing during manufacturing**	H01L 21/66	
	2.Testing after manufacturing	H02S 50/00-15	
Devices	**1. Lighting Devices**	F21L 4/00	F21S 9/03
	2. Thermal Devices (heating, cooling)	H02S 40/40-44	
Combined	Combinations of the groups above	H01L 31/00 H02S 40/00	H02N 6/00 H02S 99/00

*global subgroups (not only for PV), **mainly for the designated subgroup but might contain other cell technologies.

4. ANALYSIS AND RESULTS

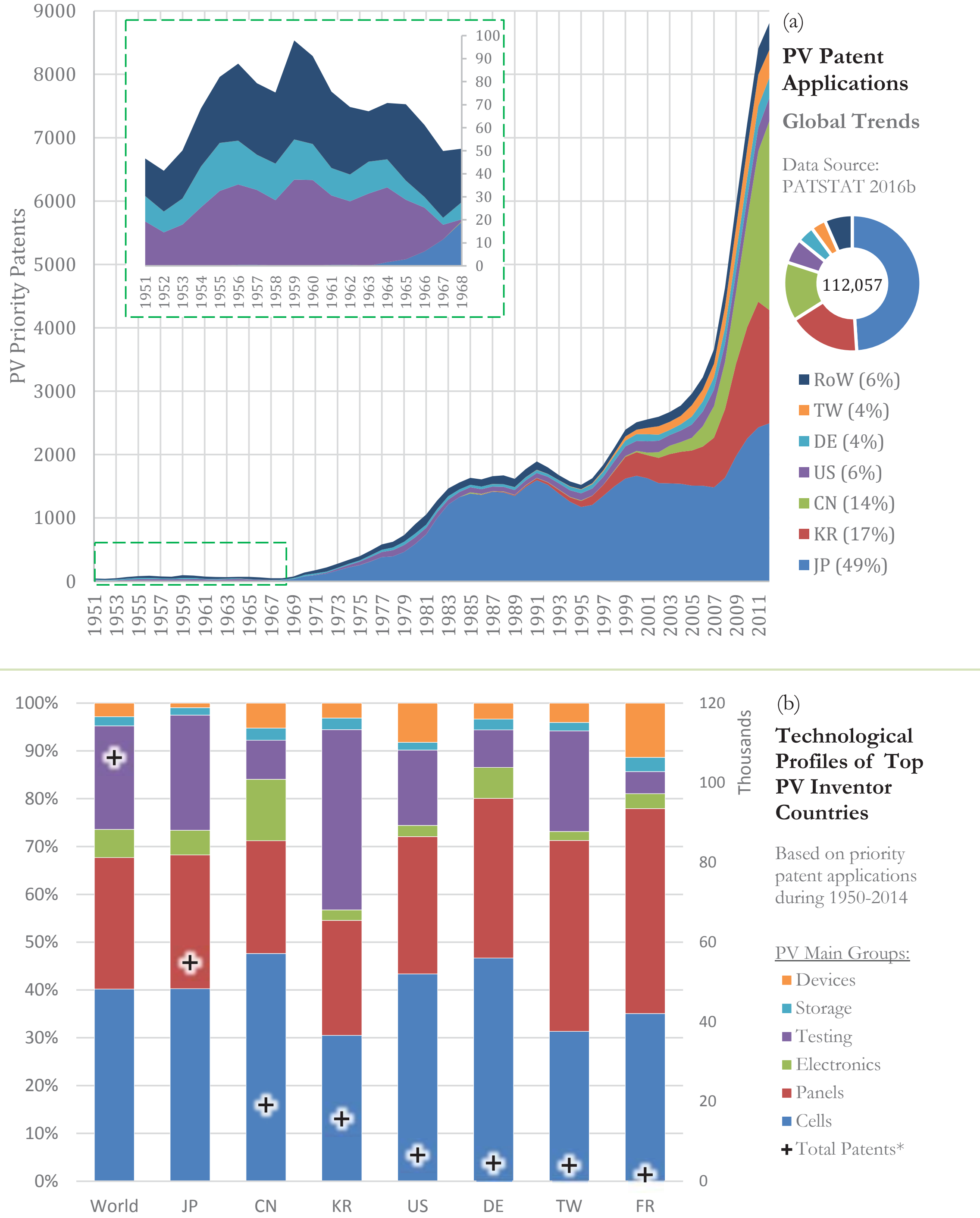
In this section, the general trends of PV patent applications are investigated, followed by a detailed consideration of the technological system development from three main perspectives: geographical, organizational, and technical.

4.1 General Trends

Landscaping the universal patenting activities in PV sector since 1950, more than 112,000 priority patent applications were found. They were filed in 73 different patent offices by around 50,000 applicants and 200,000 inventors located in 110 countries. Figure 5a shows the trends for annual counts of priority patent applications during the period 1951-2011. Patent stocks are counted based on the country of inventor as a better proxy of the location, where inventions took place. The trends show a continuous growth of patenting activities within the PV sector. Starting from low patenting levels below 100 filings per annum during 1950's and 1960's with inventors mainly from USA and Europe (esp. Germany, UK and France), a dramatic growth during 1970-1985 can be noted. Annual patents reached the level of 1,600 in 1984 then stabilised below the level of 2,000 until early 1990's. This growth was mainly driven by Japanese inventions. Despite the notable decrease in filings occurred in 1991-1994 (which can be related to the general decline in patenting activities in Japan in all fields during early 1990's [80]), a second wave of growth within the PV system occurred during 1995-2000. It was rather driven by the entry of South Korea to the PV sector. Global PV patents exceeded the level of 2,500 in 2000. Since 2006, a third and even steeper growth jointly driven by China, Korea, and Japan has raised patent applications to the level of 9,000 filings per annum in 2011. In recent years, the case of China seems prominent, as it has experienced the highest growth (average annual rate above 40% since 1997).

In what concerns the technological distribution, figure 5b shows that 39% of the global patents belongs to solar cell technologies. The solar panels group forms the second largest group with the share of 27%, followed by testing techniques (21%), and electronics (6%).

Figure 5: General Trends of PV Priority Patents



*Figures for total patents are given in secondary axis. Author's own elaboration

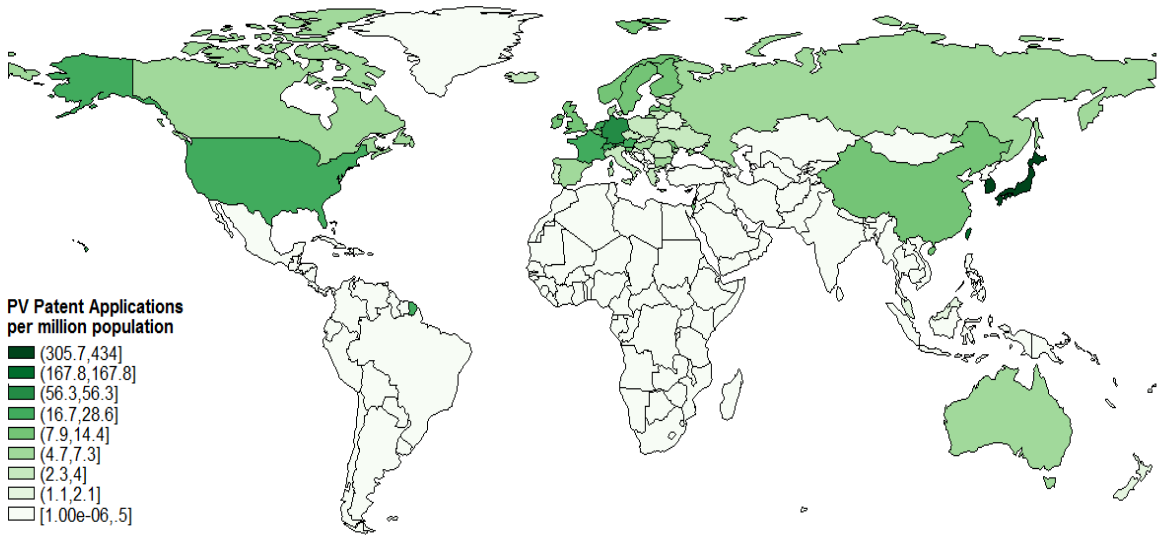
4.2 Geographical Perspective

The geographical distribution of PV priority patents as a **quantity indicator** of technological innovation is illustrated in Figures 5a and 6.

First, regarding the accumulated patent applications in the field during the full period, only seven countries were accountable for 95% of the total filings. These countries are Japan (49%), Korea (17%), China (14%), USA (6%), Germany and Taiwan (4% for each), and France (1%) (Figure 5a).

Figure 6 shows a world Choropleth map of accumulated PV patent applications per population of countries. Japan, Korea, and Taiwan hold the top per-capita PV patents of 434, 305.7, 167.8 respectively, followed by Germany (56.3), Switzerland, France, and USA (around 25 each). On the other hand, China comes at the tenth place with 14.4 PV patents per capita.

Figure 6: World Map of per-capita PV Patent Applications



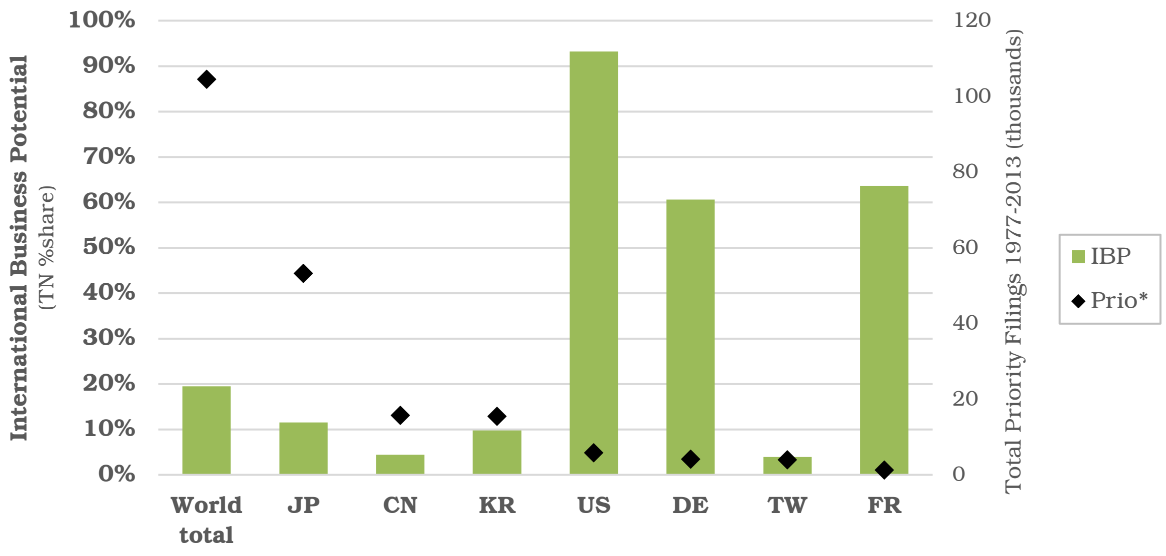
Author’s own elaboration

Regarding patent **quality** at state level, the **international business potential** indicator (IBP) is calculated for the top seven countries as well as for the World total, as shown in Figure 7.

While 20% of PV patent families contains at least one transnational application, the IBP indicator differs widely among the top inventor countries. A clear contrast in IBP values can be noted between western and eastern countries. USA, France and Germany have scored high IBP ratios (of 93%, 64% and 61% respectively), whereas Japan, Korea, China and Taiwan had modest IBP scores (of 12%, 10%, 4% and 4% respectively).

This result indicates a significant higher tendency of inventors located in western countries to protect their inventions in several international markets (across their national borders), compared to the eastern inventors, who rather tend to patent their inventions domestically. It also reveals a potential positive correlation between the country’s IBP and the economic and technological value of its patent applications.

Figure 7: International Business Potential of Top Inventor Countries



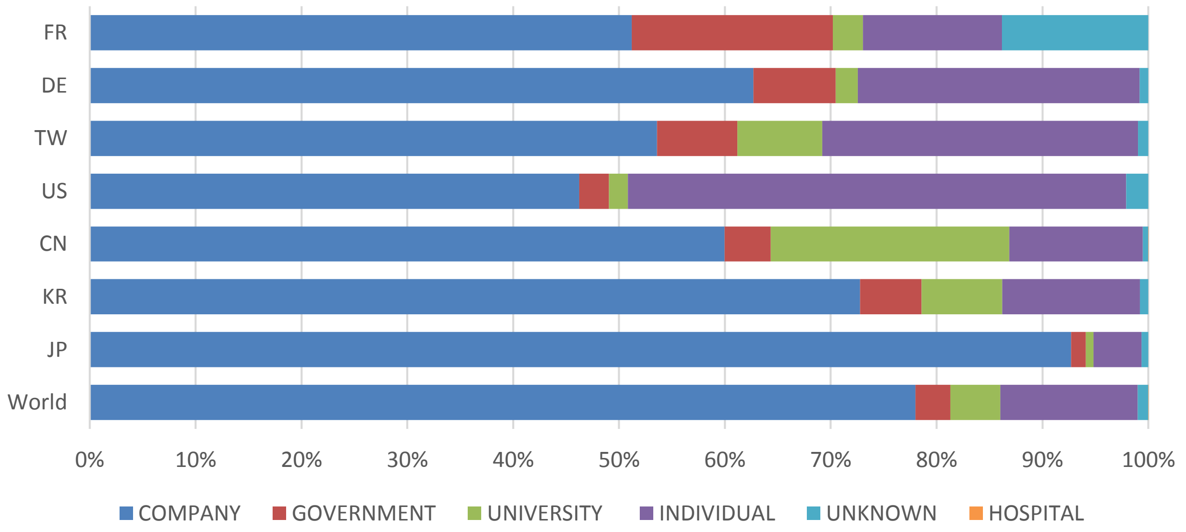
*. Priority filing figures are given in secondary axis. Author's own elaboration.

4.3 Organizational Perspective

Five organizational types were found as applicants for PV patents: private companies, public organizations (such as government owned companies and research centres), universities, hospitals and individuals. Most priority patents are filed by private companies (78%), individuals (12%), and universities (5%).

Regarding the **geographical distribution of organization types**, figure 8 shows different patterns for the top countries. While the vast majority of PV patent applicants in Japan are private companies, around 50% of the American applicants are individuals. On the other hand, universities have a prominent share in the Chinese patents (22%). In France, government owned organizations are accounted for 19% of the country's patents in the PV sector.

Figure 8: Geographical Distribution of Organization Types



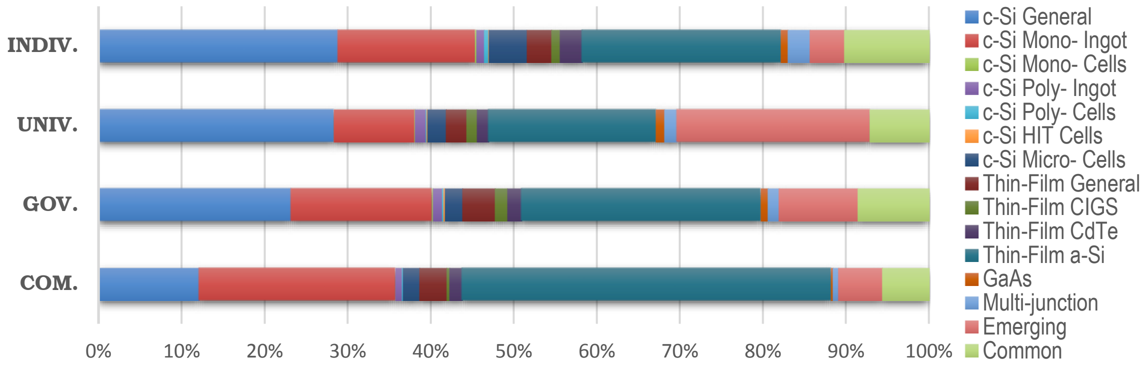
Author's own elaboration

In what concerns the **technological specialization of organization types**, Figure 9 shows the distribution of PV technologies over the identified organizational types of applicants. It shows that 45% of companies have filed patents in a-Si thin-film cells compared with 39% in c-Si technologies. State-owned organizations have a similar portfolio, however a less share of thin-film technologies is compensated with patents in c-Si and organic cells. For universities, the share of emerging and organic cell technologies seems prominent. The portfolio of individuals is more homogenous.

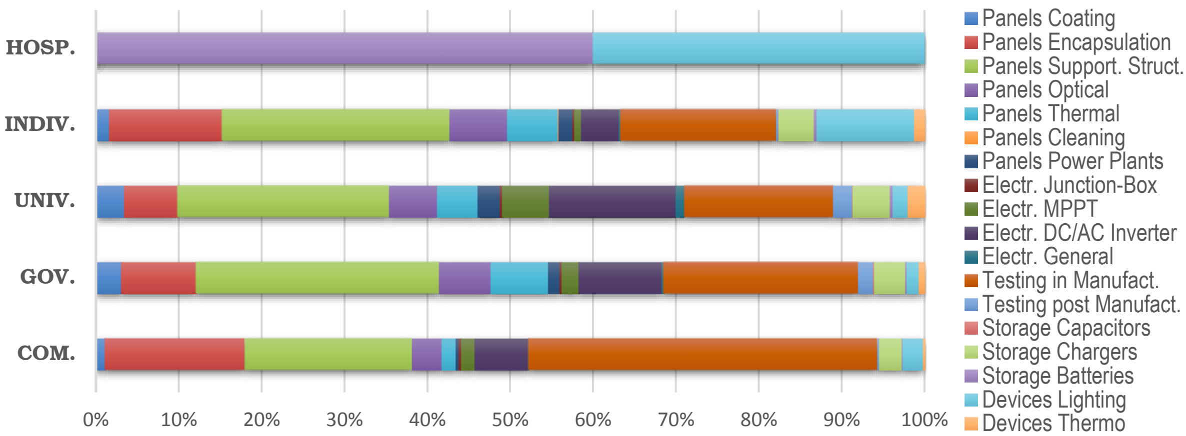
With regard to BoS technologies (figure 9b), companies have relative advantage in testing (during manufacturing) and panel technologies. Prominent share for the electronics group (MPPT and DC/AC inverters) is noted in universities. Furthermore, the portfolio of hospitals comprises patents in off-grid energy storage (batteries) and lighting devices.

Figure 9: Technical Distribution of Organization Types

(a) PV Cell Technologies



(b) PV Balance of System Technologies



Author's own elaboration

Table 3 lists the top PV patent applicants over three periods (21-year length) along with their countries and total number of patent applications. Interestingly, all actors are private companies. While western companies from Germany, USA, and UK were dominating the first period, all top applicants of the second period were located in Japan. In the most recent period, new Korean and Chinese applicants has succeeded to reach the top-ten list.

Table 3: Top-Ten List of PV Patent Applicants

Period I: 1950 - 1970			*Period II: 1971 - 1991*			*Period III: 1992 - 2012*		
Applicant Name	**Ctry.**	**Patents**	**Applicant Name**	**Ctry.**	**Patents**	**Applicant Name**	**Ctry.**	**Patents**
Siemens AG	DE	113.5	Mitsubishi Electric Corp	JP	1444.2	Sharp KK	JP	1964.7
Licentia Gmbh	DE	30.3	Hitachi Ltd	JP	1329.7	Samsung Electronics Co Ltd	KR	1781.3
Texas Instruments Inc.	US	25.2	Fujitsu Ltd	JP	1187.8	Sanyo Electric Co	JP	1287.4
Gen Electric	US	42.7	NEC Corp	JP	928.5	Mitsubishi Electric Corp	JP	1244.7
Westinghouse Electric Corp	US	23.6	Matsushita Electric Ind. Co	JP	853.4	Kyocera Corp	JP	1221.1
Bell Telephone Labor Inc.	US	22.7	Sanyo Electric Co	JP	640.1	Sony Corp	JP	598.5
Hoffman Electronics Corp	US	18.6	Tokyo Shibaura Electric Co	JP	603.0	Hynix Semiconductor Inc.	KR	588.9
IBM	US	17.2	Toshiba Corp	JP	593.3	IBM	US	305.7
Standard Telephones Cables	UK	16.0	Canon KK	JP	563.5	Taiwan Semiconductor Mfg.	TW	264.2
RCA Corp	US	15.7	Sharp KK	JP	552.4	Oceans King Lighting Science	CN	221.0

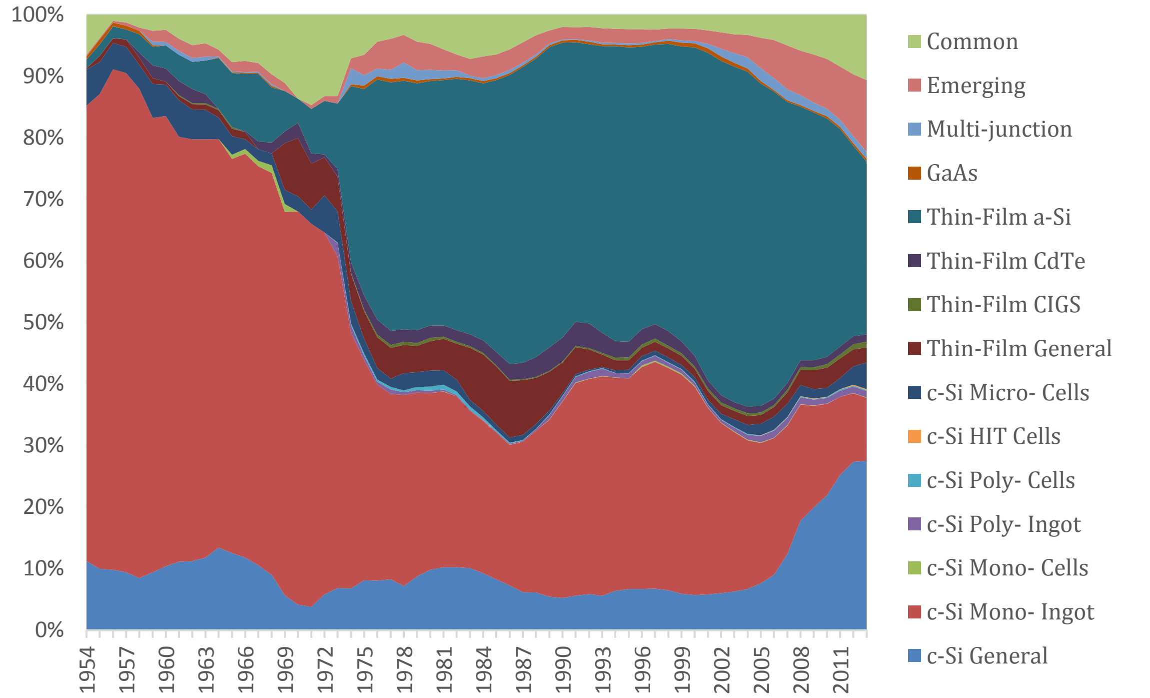
Data extracted from PATSTAT 2016b. Author own elaboration.

4.4 Technical Perspective

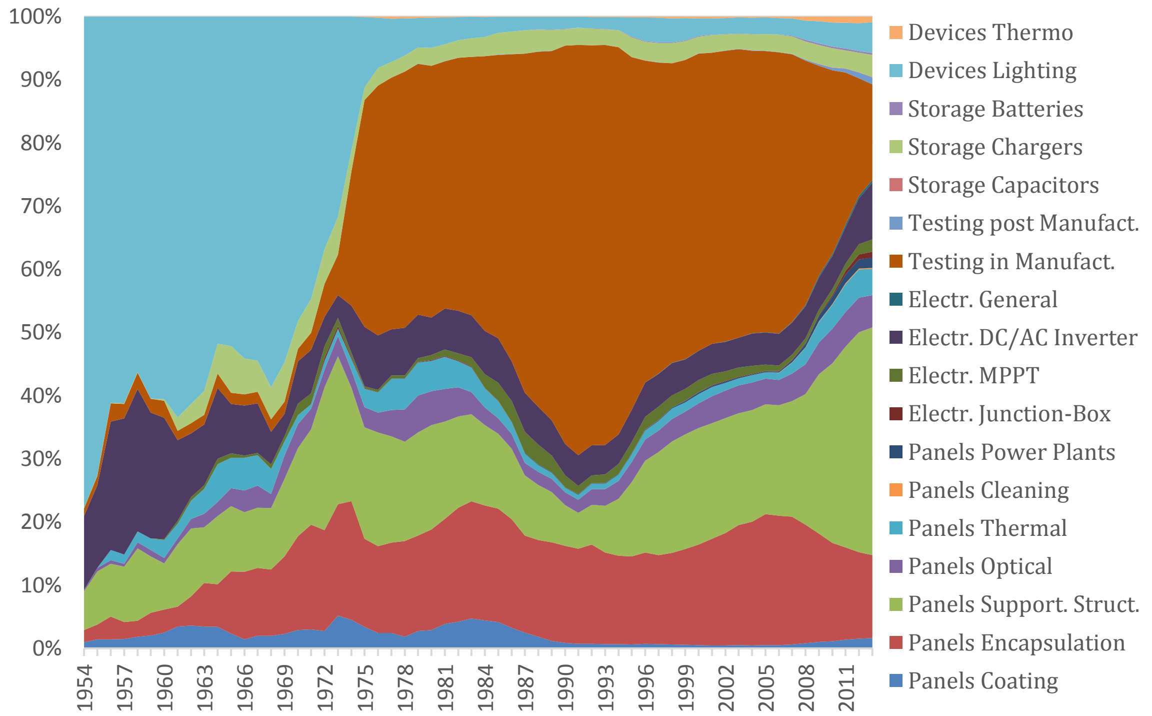
To understand the **temporal development** of the PV system from a technical perspective, the annual-share trends of each technology are shown in figure 10. It highlights the relative importance of PV technical groups over time.

Figure 10: Temporal Distribution of PV Technologies

(a) PV Cell Technologies



(b) PV Balance of System Technologies



Author's own elaboration

In respect of cell technologies (figure 10a), mono-Si ingots form the dominant technology over 1954-1974. However, since 1974, the thin-film technology of amorphous silicon has become the most patented cell technology. A growth of emerging technologies since 2001 can be noticed. Moreover, the fabrication of c-Si cells is gaining an increasing importance since 2005.

On the other hand, the landscape of BoS technologies (figure 10b) shows two major shifts in technical focus of patents. During 1954-1974, lighting portable devices held around 60% of patentable inventions. However, testing techniques (during-manufacturing) became the dominant technology over 1975-2005. Finally, a growing stream of panels' encapsulation and supporting structures can be noted since 2005.

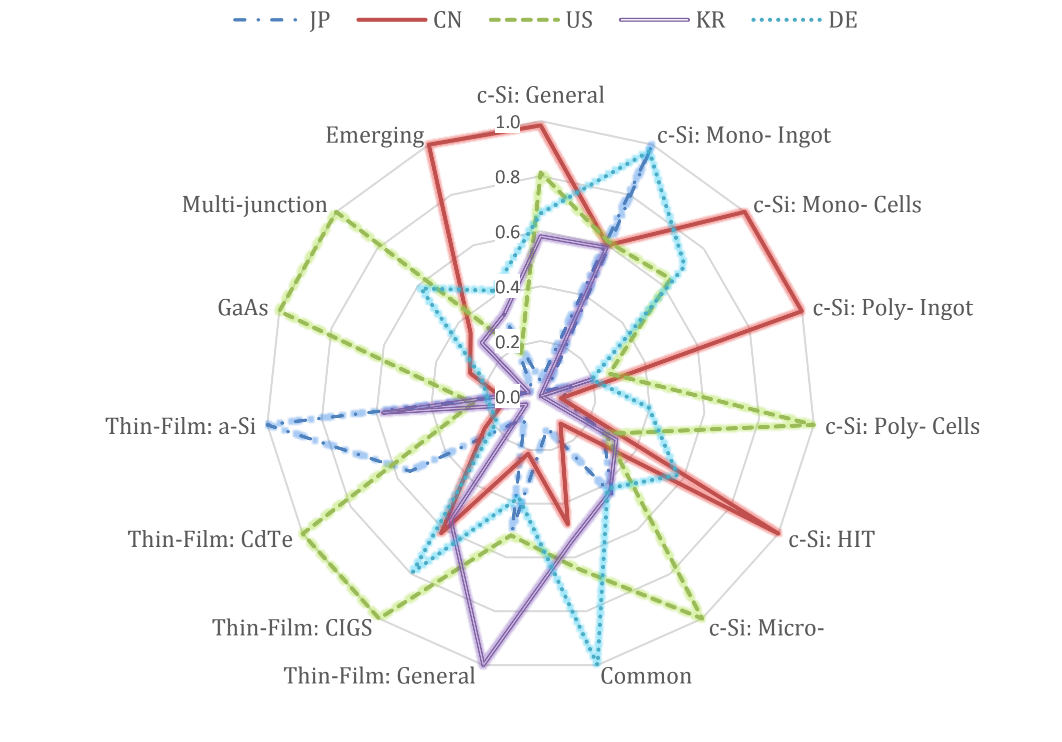
Considering the **spatial distribution** of PV technologies, the specialization profiles of the top countries are investigated. Figure 5b shows that the cells group holds more than 40% of filings in China, Germany, USA and Japan, while panels form the main specialization of France and Taiwan. On the other hand, 37% of the Korean PV patents belong to the testing and monitoring group.

Going one level deeper with the **technological specialization analysis of the top PV inventor countries**, their RTA indexes for each technological group is calculated (figure 11). The RTA values in the figure were normalized to the range of [0-1] with relevance to the maximum value in each group. For what concerns cell technologies (figure 11a), China has shown a relative advantage in c-Si cells (esp. mono-Si cells and poly-Si ingots) as well as in the emerging cell technologies. Japan and Germany have a relative advantage in mono-Si ingots. While Korea has advantage in general thin-film technologies, USA is highly specialized in CdTe, CIGS, GaAs, and multi-junction technologies. In a-Si thin film technology, Japan holds the highest RTA.

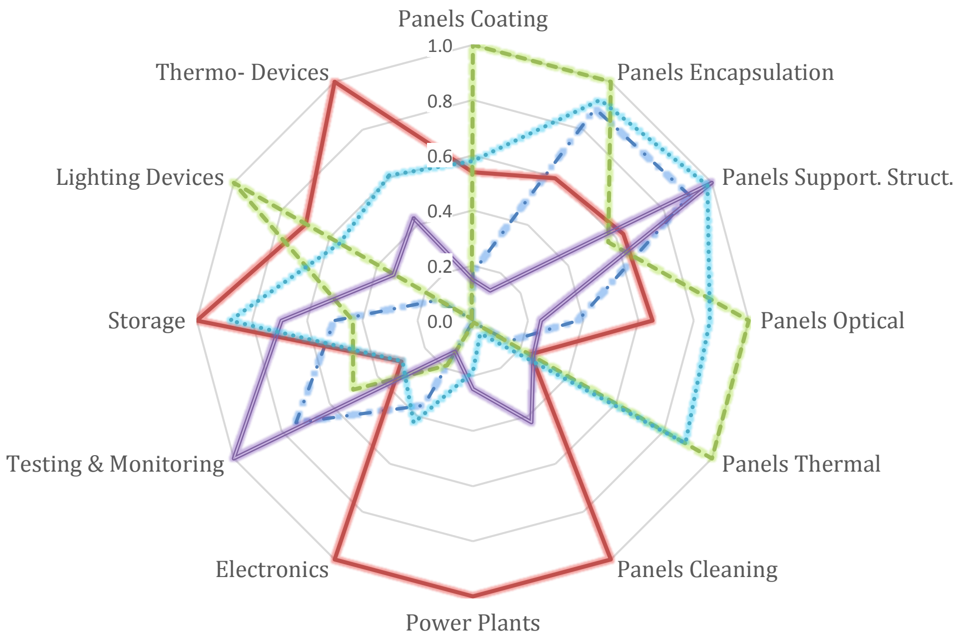
On a related front, figure 11b shows the RTA levels within the BoS technologies. While USA has a relative advantage in the coating, encapsulation, optical, and thermal groups of PV panels, China is more specialized in PV power plants, panel cleaning, electronics, energy storage and thermal devices. On the other hand, Korea, Germany and Japan have the lead in panel supporting structures.

As far as the electronics group is concerned, PV junction-box patents are mostly filed by China, while 60% of the patents for MPPT and inverter technologies are held by Japan. Testing during manufacturing is dominated by Japan, whereas post-manufacturing testing techniques are mostly patented in China. In both cases, Korea comes in the second place with a share around 25% of the patents. Internal energy storage techniques are mostly patented in Korea. The same holds for battery technologies in China and charging arrangements in Japan. Whereas a homogeneous distribution of lighting device patents is found across Japan, China, USA and Korea. Thermal devices are dominated by China, Korea and Germany.

Figure 11: RTA Specialization Profiles of Top 5 Countries



(a) PV Cell Technologies



(b) PV Balance of System Technologies

Author's own elaboration

4.5 Review of Most Influential PV Patents

This section discusses the most influential patent applications within the PV technological system (Table 4). To do so, the forward citation impact factor was first calculated for all PV patents extracted from PATSTAT over the period 1950-2015. Next, patent applications were distributed over the predefined groups of PV technological system (section 3.2.4). After that, patents with the highest PIF scores in each group were selected, for which the original publication documents were extracted from patent repositories to be technically reviewed.

Table 4: Most influential PV Patent Applications

Patent Number	Year	C_i	PIF	Ctry.	Scope
JP19930294633	1993	688	29.9	Japan	c-Si Cells
US20010975572	2001	366	24.4	USA	PV Panels
US19930173294	1993	492	21.4	USA	Monitoring
US20000527316	2000	253	15.8	USA	Thin-film Cells
US20010878523	2001	236	15.7	USA	Organic Cells
US19990454063	1999	222	13.1	USA	Multi-junction Cells
US20020217861	2002	181	12.9	USA	Optical/Thermal
US19920894879	1992	293	12.2	USA	Energy Storage
US20020067357	2002	125	8.9	USA, Taiwan	Lighting Devices
DE20091018126	2009	61	8.7	Germany	PV Electronics

Patents are sorted by their impact factors in a descending order. Data extracted from PATSTAT 2016b. Author's own elaboration.

4.5.1 Crystalline Silicon Cells

Entitled "*Method for manufacturing a semiconductor device*" [81], the most influential patent in c-Si cell technologies was assigned to the Japanese company *Semiconductor Energy Laboratory Ltd.* in 1993. The patent was filed in the Japanese and American patent offices. With its USPTO patent grant in 1995, the current legal status of this patent is '*Expired - Lifetime*' since 2015. It was cited 688 times since its publication, achieving an impact factor of 29.9.

The invention introduces a stable process for manufacturing crystalline semiconductor-based devices for electro-optical applications with high productivity. The main idea behind the invention is the crystallization of amorphous silicon film through coating it with a catalyst element and heat treating it. While the used catalysts belong to the group (Ni, Pt, Cu, Ag, Au, In, Sn, P, As, and Sb), the heat treatment is done at a relatively low temperature. Accordingly, the crystallization process through this invention can be done at temperatures of 450-550°C for a duration of around 4 hours, compared to 600°C for 10 hours in the prior state-of-art.

4.5.2 Thin-film Cells

Under the title "*Fabrication of thin-film, flexible photovoltaic module*", the *University of Delaware* (USA) in cooperation with three other American companies (*Microsoft Corp, Global Solar Energy Inc.,* and *UD Technology Corp*) has filed the most influential patent within the thin-film PV group in 2000 [82]. The invention was made with government support through a fund from the Defense Advanced Research Projects Agency (DARPA) in the USA. The current legal status of the patent is 'Grant – Active'. However, its expiry is expected in April 2022. Being filed in the USPTO, its grant publication (No. US6372538B1) has been cited 253 times (PIF=15.8).

The invention introduces a new structure and manufacturing procedure of flexible thin-film PV cells (esp. CIGS and CdS cells). The procedure comprises roll-to-roll continuous chamber-segregated process, multi-material vapour-deposition, as well as evaporation. Additionally, the patent covers a unique vapour-creating system (heated crucibles with nozzle sources of metallic vapours) and a comb-like material distributing system. The main contributions of this invention to the prior state-of-the-art are related to large scale production possibilities through the automated roll-to-roll processing of flexible substrates. Accordingly, it results in a less expensive, faster, and more robust manufacturing process.

4.5.3 Multi-junction Cells

The patent entitled "*Multijunction photovoltaic cells and panels using a silicon or silicon-germanium active substrate cell for space and terrestrial applications*" (EPODOC No. US19990454063) has been cited 222 times since its priority application in December 1999 [83]. With an impact factor of 13.1, the patent is considered in this analysis as the most influential patent application within the 3G multi-junction PV cells. It is assigned to the American company Hughes Electronics Corp. Its current legal status is 'Grant – Active'. Furthermore, its patent family contains applications to the USPO and EPO.

Technically, the invention introduces a solar PV cell structure of multiple layers whose bandgaps are different in order to absorb as much as possible of the sunlight spectrum. Accordingly, the cell consists of an active substrate (Si or Si-Ge), on which several (upper and lower) sub-cells are disposed. The design guarantees that the upper sub-cells have greater bandgaps than the substrate's. Besides supporting the cell structure, the active substrate provides PV current density and voltage. Since the junctions are series-interconnected, the sub-cells are designed to match the substrate's PV current density. Additionally, the patent provides different designs and materials for the cell substrate and sub-cells. With relevance to the prior state-of-art, the inventors claimed an improved conversion efficiency, yield, and cell adaptability to different applications. Such characteristic makes the invented cell more suitable for space applications. With higher conversion efficiency per PV cell, fewer cells are required, resulting in a cost reduction of cells and supporting structures. The higher efficiency can also result in less waste heat, i.e. lower cells temperature and further improvements in power output.

4.5.4 Organic Cells

In 2001, the Trustees of Princeton University filed a patent application entitled "*Organic photovoltaic devices*" at the USPTO [84]. It was followed by similar applications at the EPO, Japanese, Korean, and Chinese patent offices, as well as an international patent application under the PCT in 2002. The patent has received 236 citations, resulted in an impact factor of 15.7.

Technically, the invention introduces organic photosensitive devices for generating electrical energy out of light. The introduced PV cells comprise multiple stacked sub-cells that are interconnected in series. The operation principle is based on the absorption of photons energy in the sub-cells, resulting in the generation of excitons that can diffuse in the organic films. Dissociation of the excitons takes place at a heterojunction of copper phthalocyanine (CuPc) and perylenetetracarboxylic-bis-benzimidazole (PTCBI). Consequently, holes are transported in the CuPc layers and collected by ITO electrode, whereas electrons move in PTCBI to be collected by a silver cathode. Additionally, recombination of electrons and holes takes place in an intermediate silver layer. As stated in the patent application, the invention contributes with improved conversion efficiency (>4%) along with thickness optimization through an electron blocking layer technology.

4.5.5 Panel Encapsulation & Supporting Structures

With 366 citations and a PIF of 24.4, the patent entitled "*Solar module mounting method and clip*" is the most influential patent within the solar panels group [85]. It was applied for by an American inventor called Jefferson Shingleton in 2001. The patent family contains a domestic application at the USPTO and an international PCT application.

The invention introduces a solar panel supporting system consisting of a sheet metal frame, on which the panels are mounted by butyl tape. Additionally, clips for clamping the panels to the support beams are used. These clips comprise T-shaped upper portions, channel nut retainers, and threaded holes with bolts. Furthermore, the electrical wires of panels and junction boxes as well as the mechanical fasteners are concealed within the beams. The invention claimed to provide a low-cost technique for attaching several types of unframed PV modules to different supporting surfaces making it more practical and economically efficient than the prior state-of-art.

4.5.6 Panel Optical & Thermal Arrangements

Within the optical and thermal arrangement of solar PV panels, the patent entitled "*Concentrating solar energy receiver*" [86] is found to be highly influential, as it has been cited by 181 patent and non-patent publications since its priority date in 2002 (PIF=12.9). The application is assigned to an American individual called Bernard Bareis. The patent family contains applications at the USPTO, EPO, Chinese patent office, and a PCT application. However, the current status of the patent is 'Expired - Fee Related'.

Technically, the patent discloses a concentrating solar receiver consisting of a primary parabolic reflector and a highly reflective surface with an extending focal axis from its concave side passing through the focal point of the primary reflector. The module reception surface is thus spaced from the focal point by a predetermined distance. This conversion module contains both a PV array and a coupled surface with thermal cycle engine whose mechanical output is used for driving an electric generator.

The invention claimed to have advantage over the conventional concentrating solar energy receivers (prior state-of-art) in two aspects. First, it provides a less heat concentration in the focal point region. Secondly, it captures the large infrared portion of radiant spectrum and converts it into electricity through the thermal cycle engine and electric generators. Therefore, it eliminates the negative effect of such excess heat on the conversion efficiency of the PV cells.

4.5.7 Electronic Technologies - General

Under the title "*Energy supply system and operating method*" [87], the German research institute *Zentrum für Sonnenenergie und Wasserstoff-Forschung Baden-Wuerttemberg* has filed a PV electronics patent application in 2009. The patent family includes applications at the German, Spanish, Danish, Canadian, and American patent offices, as well as the both transnational types: EPO and PCT. The current status of the patent is 'Grant - Active'. It has been cited 61 times since its publication (PIF=8.7).

Technically, the invention introduces an energy supply system with regenerative-electricity generating device feeding the supply grid. It also includes an electrical device for generating hydrogen from the regenerative power, along with a device for hosting a chemical reaction between the generated hydrogen and carbon oxide gas supply. The reaction aims at producing methane gas to be fed into the gas supply grid.

The invention claimed to address the fluctuating nature of renewable energy sources.[19] It hence contributes with a supply system that ensures stability and reliability, while having a significant part of its generated electricity coming from renewable sources. The claimed novelty in this invention is related to the idea of connecting the electricity- and gas supply grids together through generating devices. It suggests converting the excess renewable energy into gas supply through an electrically initiated reaction between H_2 and CO_2 (i.e. the storage of excess renewable energy into the form of fossil fuel). Such idea sounds promising given the climate change and energy challenges.

4.5.8 Battery Recharging Circuitry

Under this category, the American company *Micron Technology Inc.* has filed a patent that received 293 citations since its priority date in 1992 (PIF=12.2). It is entitled "*Passive (non-contact) recharging of secondary battery cell(s) powering RFID transponder tags*" [88]. The current status of the patent is "Expired – Lifetime ".

Technically, the invention introduces a recharging method of remote battery cells in radio frequency identification (RFID) devices. The invention is thus particularly related to battery backed transponders. It presents a passive (non-contact) recharging circuitry. The

[19] i.e. the fact that PV and wind energy widely varies over the time of the day, season and weather conditions.

energy sources of such passive recharging strategy include external radio frequency signals, seismic geophone, seismic piezoelectric accelerometers, external PV cells, internal heat infrared PV cells, and acoustic energy.

4.5.9 Process Monitoring

Filed in 1993 by the American company *International Business Machines Corp*. (*IBM*), the patent "*In-situ endpoint detection and process monitoring method and apparatus for chemical-mechanical polishing*" [89] has been cited 492 times (PIF=21.4). Its current legal status is "Expired – Lifetime". The patent family contains applications to the USPTO, EPO, German, and Japanese patent offices.

Technically, the invention has put forward a design of a monitoring apparatus for chemical-mechanical polishing processes of silicon wafers. While the polishing machine consists of a rotatable table and a polishing slurry, the introduced apparatus comprises an embedded window within the rotatable table. Accordingly, the window enables a clear view of the polishing surface during manufacturing process. Furthermore, the apparatus contains measurement means of reflectance underneath the polishing table. Changes in reflectance signals indicate relevant changes in the polishing process conditions. The patent claimed contributing with an accurate and efficient real-time detection technique that instantly monitors polishing characteristics of the chemical-mechanical planarization process. Consequently, it was considered to result in semiconductor wafers of higher quality than those of the prior non-monitored processes. Additionally, the presented invention facilitates automated manufacturing processes, and hence mass production.

4.5.10 Portable Devices: Lighting System

The patent entitled "*Solar energy-operated street-lamp system*" [90] has been cited 125 times since its priority date in 2002 (PIF=8.9). It was filed at the USPTO by a Taiwanese inventor called Chao Hsiang Wang. Its current legal status is "Expired - Fee Related".

Technically, the invention introduces a street-lamp device powered by solar PV energy. It comprises a PV module (solar absorption board), an electronic circuit board, and a battery mounted within the lamp-post for energy storage. Furthermore, light emitting diodes LEDs are connected to the circuit board. The PV module's board is covered with a transparent protective hood. The hood is designed in an arc-shape so that fallen leaves or dust particles do not stick on its surface.

5. DISCUSSION AND CONCLUSIONS

The present article has put forward a comprehensive patent analysis of solar PV technologies over the past six decades. To do so, it first defined the PV technological system distinguishing between different solar cell and balance of system technologies. It has further introduced a methodical approach for precisely identifying patent applications relevant to the system making them directly capturable with IPC classes.

Consequently, the introduced classification allowed for a clear differentiation within the PV system between electrical-, mechanical-, as well as chemical micro-technology based knowledge. It defined the PV technological system to comprise six main groups: solar cells, panels, electronics, energy storage, testing and monitoring techniques, as well as portable PV-powered devices.

Using the PV technological system definition (section 2), its relevant priority patent applications were identified through a sequential procedure of IPC identification, verification, validation, and technical assignment processes (section 3). Comparing with the prior state-of-art, the proposed approach has shown a high level of data completeness, relevancy and simplicity.[20] Furthermore, its significance lies in the detailed utilisation of the IPC system at the highest possible resolution.[21] This allows for capturing technological innovations at various levels of the PV value chain and bridging the gap between scientific and market sides of the technology.

Based on the classification, the geographical, organizational and technical trends of PV global patenting were discussed, followed by a review of the most influential inventions (section 4). The results reveal interesting findings regarding the three perspectives:

Geographically, the analysis shows that 95% of PV patents were filed by inventors in seven countries: Japan, Korea, China, USA, Germany, Taiwan, and France. Despite the higher quantity of patent applications filed by east Asian countries, the international business potential of their patents is still far behind their Westerner counterparts.

The organizational analysis indicates a significant importance of private companies in filing PV patent applications. However, other types of organizations play important roles in some countries, such as individuals in the USA and Germany, universities in China, and public research institutes in France.

In terms of technological specialization, China mostly focuses on the 1G c-Si cells, while Korea, Japan, and USA have relative advantage in the 2G thin-film technologies. Regarding the efficient technologies of GaAs and multi-junction cells (3G), USA has been the main innovator so far. The technical analysis further shows two main shifts in the patenting focus, first in 1974 from the purification of mono-silicon to the thin-film technology of a-Si, and second to the fabrication of c-Si cells since 2005 (mainly driven by China). This has been accompanied by a shift from lighting devices towards monitoring techniques, and later on towards solar panels.

Based on a forward citation impact factor analysis, the paper has identified ten patent applications belonging to the various PV groups as the most influential innovations. The technical review of these patents has shown the global continuous efforts for improving PV technologies and addressing their technical challenges.

Taken together, the results show that the PV technological system has been deeply connected with patenting activities since its emergence in the past century. Besides its

[20] While some of the already available identification methods are very difficult to be re-applied with other datasets or time periods, the introduced definition is fully replicable because it is based on IPC subgroups that are used by almost all patent offices worldwide.

[21] i.e. the 5th level of classification comparing to only 3 levels used in prior state-of-the-art.

growing global trends, the significant relation between the PV sector and patenting activities can further be illustrated by two observations: The first is the numerous radical PV inventions that were initially filed in patents (e.g. Siemens reactor, HIT cells, and DSSC). Second, the analysis shows how the expiry of key patents has opened windows of opportunity for new emerging countries to catch-up with the technology.

However, given the fact that patenting is not the most common publishing medium of scientific achievements in academia, the sole reliance on patent indicators cannot tell the full story. A further consideration of other scientific publication methods such as journal articles and technical reports can enhance the analysis providing clearer insights into the incremental developments of PV technologies. Another critical remark to be mentioned here is related to the use of PIF as a quality indicator for identifying the most influential patents. While the indicator succeeded in identifying important contributions and inventions across the various PV technologies, other essential patents were not captured (e.g. Siemens reactor, and DSSC). Accordingly, additional quality indicators besides the forward citation impact factor can be used in future research, such as patent family size, patent generality, originality, radicalness and accumulated citation indexes.

As discussed in the introduction, there have long been three main barriers against the heavy energy transition into renewable sources (such as PV). The barriers are: the costs, energy density, and erratic fluctuating nature of such energy sources. Nonetheless, the present article shows that technological innovation can significantly contribute in addressing all these challenges. On the one hand, the continuous improvements in PV cell conversion efficiencies, the introduction of faster, cheaper and more efficient manufacturing processes, and the development of automated fabricating, testing and monitoring techniques can all contribute in reducing the final product costs as well as improving its energy density. On the other hand, in what concerns the fluctuating nature of renewable energy, innovations (such as the patented system introduced in section 4.5.7) can contribute to provide a uniform supply of renewable generated energy.

Nonetheless, against the pressing challenges of climate change and fossil fuel depletion, technological innovation alone is not enough. A further role of policy makers, economists, and social scientists is very vital. Such role includes the design and implementation of efficient subsidizing policies for renewable energy sources, feasibility studies of relevant projects, promoting of technology adoption and global regulatory legislations. Since the consequences of energy challenges are global, their solutions need to be global as well: geographically, organisationally, and multidisciplinary.

All in all, the present article attempted at reviewing the global trends and advances in solar PV using patent indicators. Despite patents can reduce the freedom-to-operate in front of several manufacturers, they, nonetheless, can strongly indicate the technological development in the broader context and over long periods of time. Even with the several milestones yet to be achieved, solar PV technology is widely considered as a promising energy source for a sustainable future. Besides its vital role in the earth's ecosystem, photosynthesis, warmth, and light, the sun does still have much more for us to offer.

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